Free Space Laser Communications

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Outline of Presentation

- Fundamentals
- Spacecraft Technology
- Ground Reception Systems
- Simplified Link Calculation
- Recent Demonstrations
- Future Demonstrations

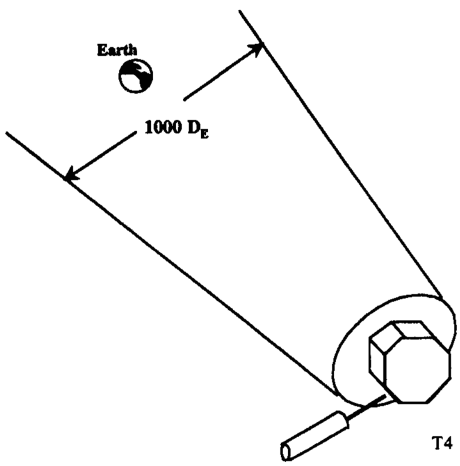
Fundamentals
Free Space Propagation

- Electromagnetic beams diverge at rates at least as fast as λ/d (Diffraction-limit)
  - λ is the wavelength of the radiation
  - d is the diameter of the transmitting aperture
- RF wavelengths usually in the cm-m range
- Optical wavelengths are in the μm range
- The more wavelengths across the aperture, the more narrow the beam divergence

T4 3

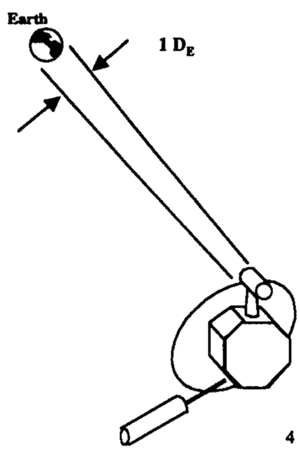
Deep Space Communications
Beam Spread

Voyager (X-Band) at Saturn
(3.8m S/C Antenna)



T4

Optical at Saturn
(10 cm Telescope)



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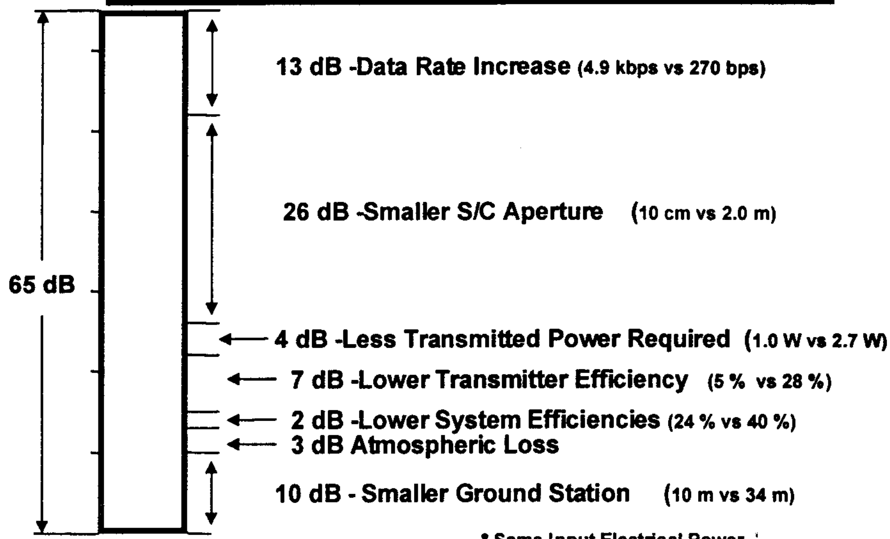
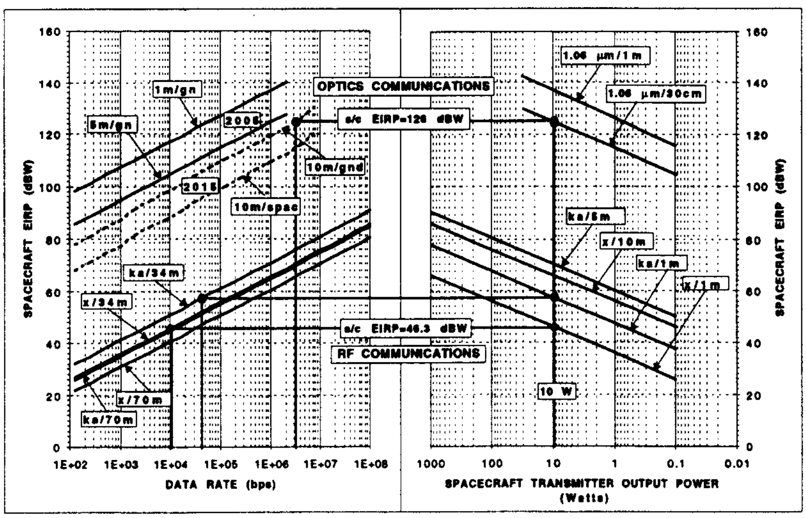
Optical Advantage Relative to Ka-Band
(Based on a Pluto FB Example)*



* Same Input Electrical Power

T4 5

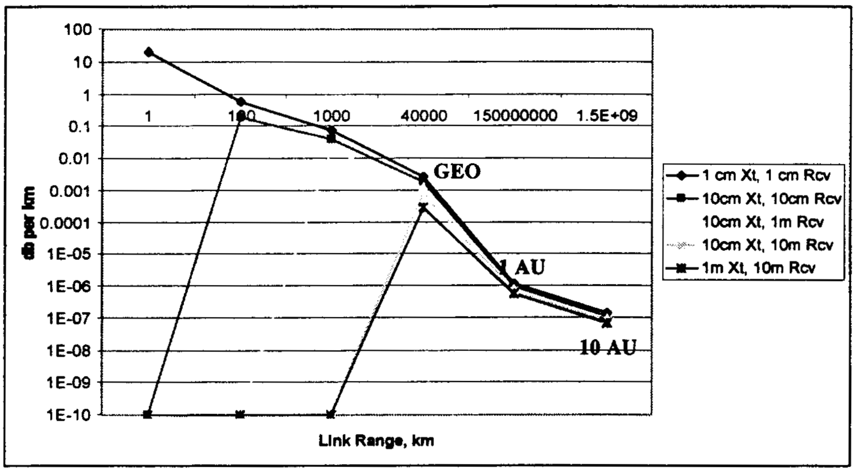
Comm Link Nomograph
Earth-Mars range: 2.5 AU



T4 6

Fundamentals

Equivalent dB/km Loss for Free Space



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Fundamentals

Good News/Bad News

- Good News:
  - Optical beams are more narrow
  - Concentrate transmitted energy on target RCVR
- Bad News:
  - Optical beams are more narrow
  - Narrow beams must be more precisely pointed
  - Must track beacon signal from intended receiver

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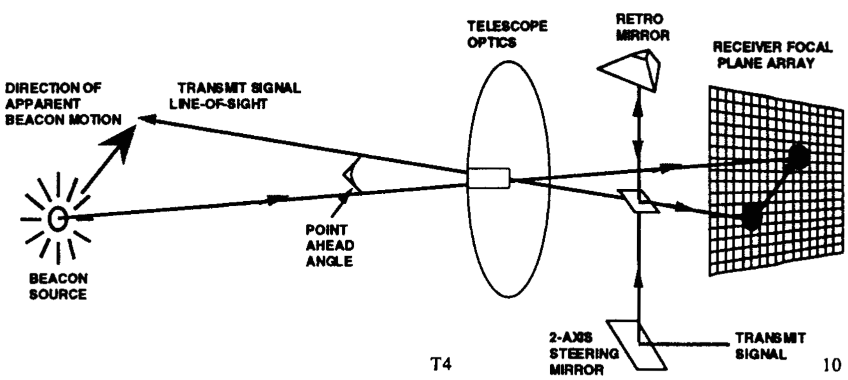
Spacecraft Technology

T4 9

Optical Communications Demonstrator (OCD) Simplified Optical Design

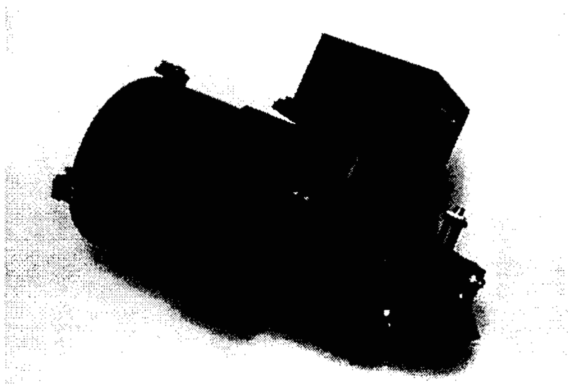
- Uses only one steering mirror and one detector array for all beam control functions
- Eliminates many beam relay optics and need for large optical bench
- All optics are located on telescope body
- Fiber-coupled laser transmitter signal removes laser heat from optics



T4 10

Optical Communications Demonstrator

Telescope Optical Assy (TOA)



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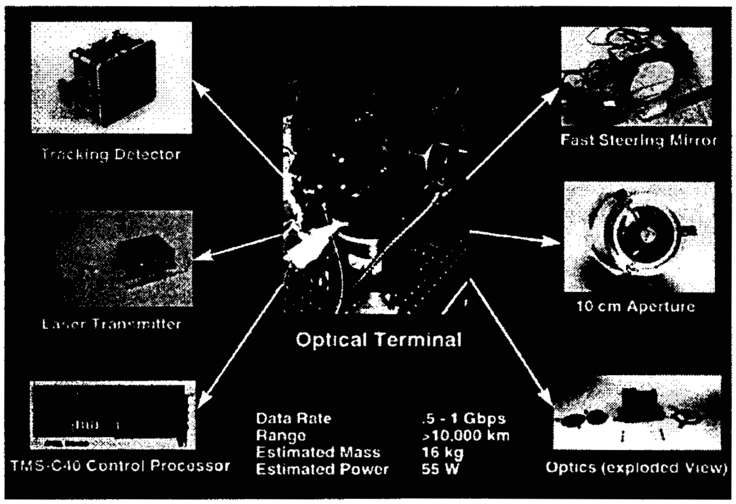
Optical Communications Demonstrator

Terminal

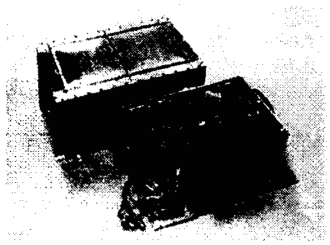


T4 12

OCD with Electronic Assy

Telescope Optics Assembly (TOA) on gimbal

Control Electronics and Enclosure



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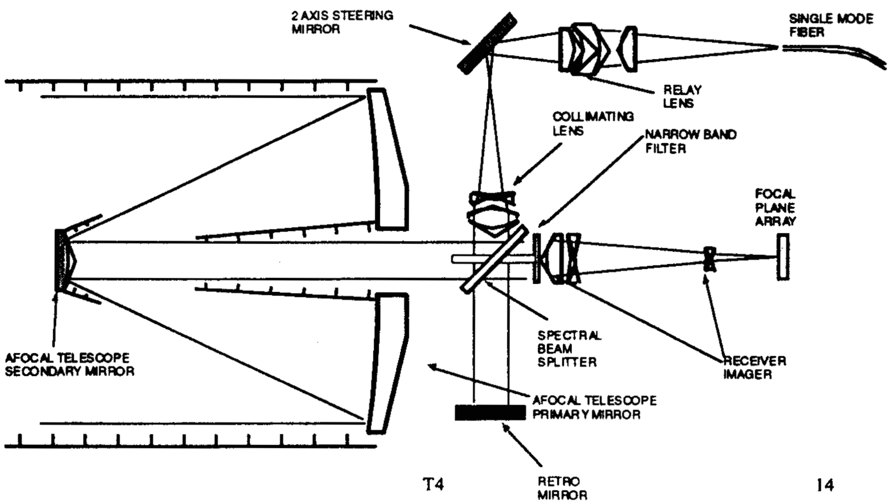
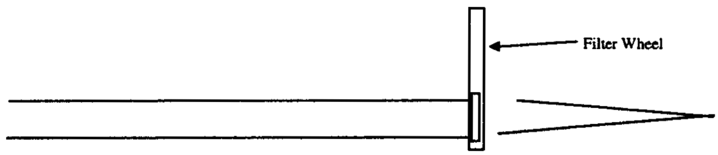
Optical Communications Demonstrator

Optics Layout

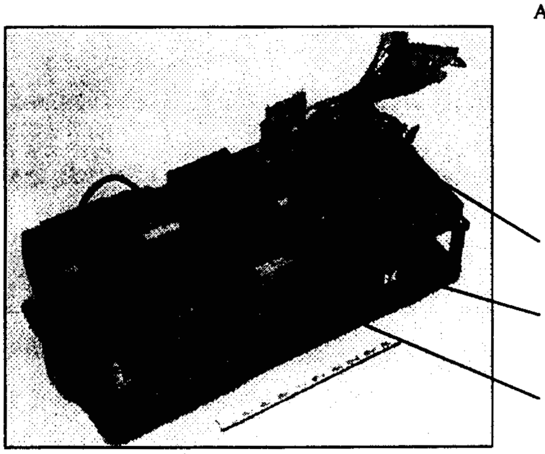


T4 14

(With Imager)



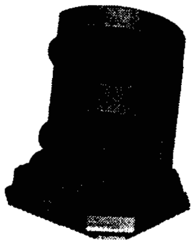
ACLAIM Breadboard Terminal



ACLAIM
- Laboratory breadboard terminal
- Overall dimensions:
  (4" x 4" x 8")
- Built from COTS parts
- Demonstrates camera/opt comm
- Part of microspacecraft breadboard

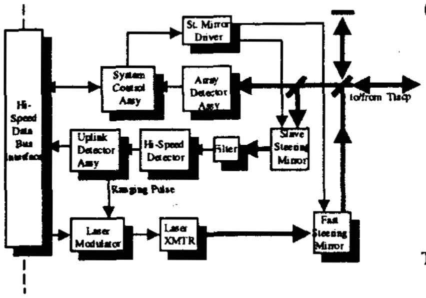
X2000 Program

Optical Comm Subsystem



Multi-Function Uses:

- Optical Comm (uplink and downlink)
- High-Resolution Imaging
  - Science Images
  - Optical (Image-based) Navigation
- Laser Altimeter Reception
- Uplink Ranging Reception
- Downlink Ranging Transmission



Communications Characteristics:

- Beacon Laser Tracking out to 1 AU
- Earth-Image Tracking Beyond 1 AU
- Redundant Critical Components
  - Lasers, Detectors, Steering Mirrors, Electronics
- >100 kbps (daytime reception)*
- >300 kbps (nighttime reception)*
- Mass < 13kg   • Power < 38W

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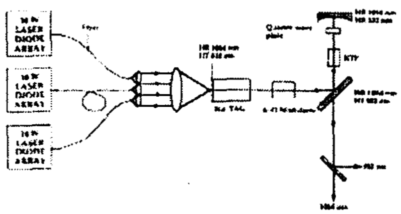
* From Europa to a 10-m Photon-bucket Receiver

JPL

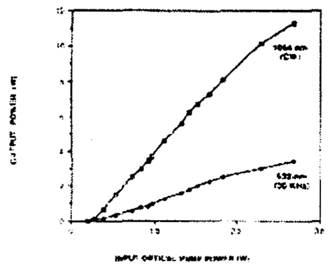
2-WATT LASER DEVELOPMENT

- DESIGNED & DEMONSTRATED A MODULATED, SOLID-STATE GREEN LASER SOURCE.
  - GOAL: 2 W OF GREEN AT 50 KHz PULSE RATE
  - ACHIEVED: 3.5 WATTS (11.7 WATTS CW AT INFRARED WAVELENGTH)
- USES THREE 10-WATT FIBER-COUPLED DIODE-LASER-BARS AS PUMP
- SEVERAL COMMERCIAL COMPANIES INTERESTED IN DESIGN



SCHEMATIC DIAGRAM OF THE SET-UP

PICTURE OF THE SET-UP



OUTPUT POWER VS. INPUT POWER

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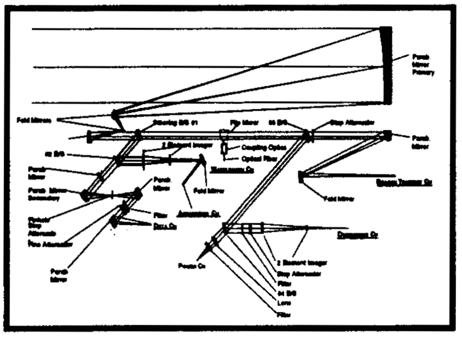
Lasercom Test and Eval Station

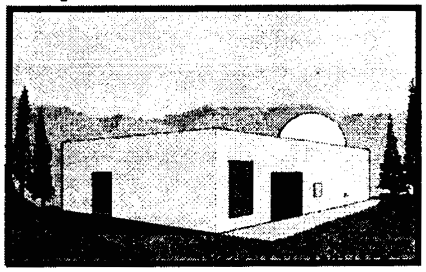
- **LTES is a high optical quality instrument that characterizes the performance of laser communications terminals (LCT's)**
  - **Measures beam divergence, acquisition and tracking performance, optical output power, and BERs of LCTs up to 1.4 Gbps data rates**
  - **Appropriate exchange of beamsplitters and detectors allows spectral operating range to extend from 0.5 μm to 2 μm**



Ground Reception Systems

1-m Optical Comm R+D Facility

- Optical Comm Telescope Laboratory (OCTL)
- Located at JPL's Table Mountain Facility
  - 2.4 km (7400 ft) elevation
- 1-m diameter aperture
- Fast (Earth-orbit) tracking mount
- Completion at end of 2000



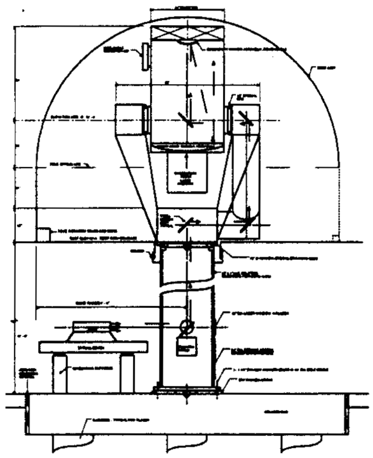


Figure 1a. Telescope Conceptual Drawing (not to scale)

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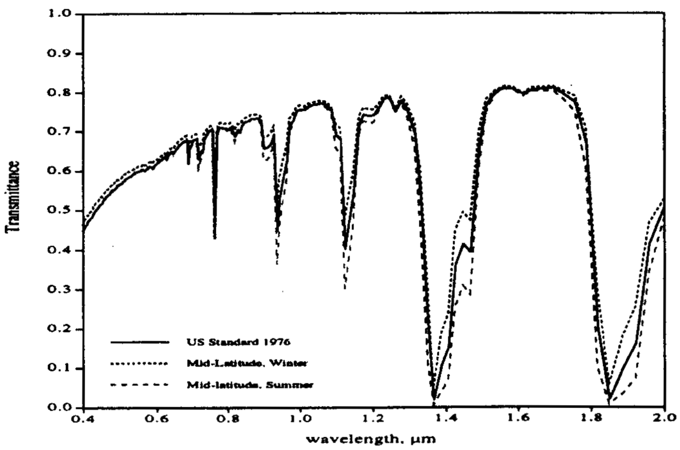
Atmospheric Transmission

Clear Weather



T4

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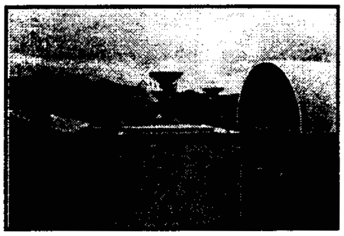
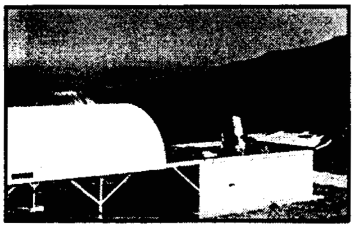
Atmospheric Visibility Data

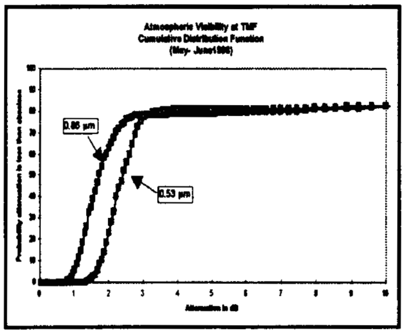


- AVM Observatory at Goldstone, CA



- AVM Observatory at Table Mtn, CA

- Visibility Cumulative Distribution



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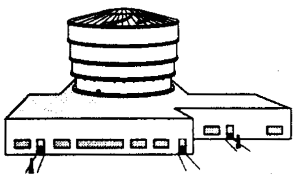
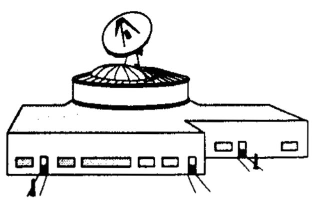
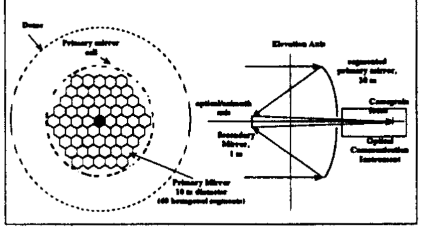
Deep Space Reception Station





- 10-m collection aperture
- Photon bucket (non-diffraction-limited)
- Segmented primary mirror

Primary Diameter, m	10	FOV at Detector, mrad	0.1
FOV at Cassegrain Focus, mrad	2.0	Fine Pointing Accuracy, mrad	0.01
Coarse Pointing Accuracy, mrad	0.2	Blur Diameter at Focus, mrad	~0.1



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Simplified Link Calculation

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Simplified Link Calculation
(Signal Level at Receiver)

- Calculate transmit beam divergence, $\theta = \lambda/d$
- Calculate spot diameter, Z, at target R meters away using $Z=R^*\theta$
- Calculate area of illuminated spot ($\pi Z^2/4$)
- Area of receiver = $\pi D^2/4$ (D=receiver diameter)
- Propagation loss (L_s) is fraction of signal intercepted (receiver area) relative to total spot area = D^2/Z^2
- Received power P_r (Watts) = $P_t{*}L_s{*}T_a{*}T_{to}{*}T_{ro}$
  - P_t = Transmitted power - T_a = Atmospheric Transmission
  - T_{to}= Transmit Optics Thruput - T_{ro}= Receive Optics Thruput
- Received signal rate = Pr/(hv) (photons/sec)

$$hv = \frac{2e\text{-}19}{\lambda \text{ (in microns)}}$$

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Simplified Link Calculation
(Background Level at Receiver)

- Background Effects
  - Point source interference signals produce a background flux rate over the receive aperture and over a spectral bandwidth (Watts/ m^2*nm) if in the detector field-of-view
  - Distributed sources (e.g. daylight) provide a background flux rate over the receive aperture over the entire field-of-view of the receiver (Watts/ m^2*nm*Sr)
  - Background signals are limited by narrow band filters of BW (in nm) and by detector FPV (in Sr)
  - Received background power (P_b) = background flux level*Receiver area*filter BW (*FOV if extended source)
  - Background Noise rate = P_b /(hv) (in photons/sec)

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Simplified Link Calculation
(Detection Performance)

- Signal Detection (performance depends on type of detector, coding, and background levels)

Receiver Type	Sensitivity
Inexpensive Receiver	> 100 photons/bit
State-of-the-Art Receiver	~ 10-20 photons/bit
Low Background/Low Rate Rcvr	< 1 photons/bit

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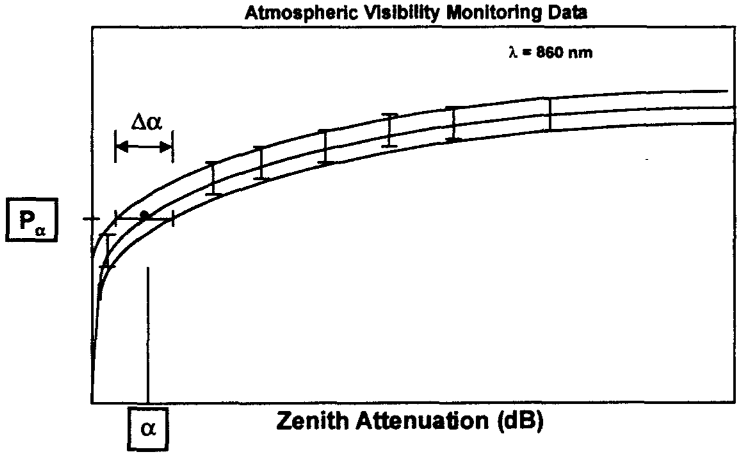
Comparison of Optical and RF Links

- Optical links are often compared to RF links
  - Need to use a common comparison basis
  - But, optical and RF have some fundamental differences
- Weather affects RF and optical systems differently
  - RF links experience weather fades infrequently
  - Optical must consider spatial diversity reception from the start.
- Need to develop an optical link design methodology that enables comparison with RF but allows for uniqueness of the two technologies

T4 29

Optical Weather Statistics

Atmospheric Visibility Monitoring Data



Zenith Attenuation (dB)

α = atmospheric attenuation; Δα = attenuation uncertainty; Pα = prob(attenuation < α)

Note: α must be adjusted for operational wavelength based on known (LOWTRAN) models (if different from measured wavelengths), and for elevation angle

T4 30

Optical Weather Model

- Atmospheric attenuation (α) is a continuous distribution ranging from low values (clear conditions) to very high values (due to clouds)
- Cloud outages impact "Station Availability"
  - Mitigated by station diversity
- Need to define what "outage" means
- Recommendation
  - Use AVM data to define atmospheric model
  - Select a value of α and the corresponding value of (P_α)
    - P_α = Probability that attenuation < α
    - Must be corrected for wavelength and elevation angle
  - Approximate the AVM distribution by two states
    - < α means clear (but with some attenuation)
    - > α means (totally) obscured by clouds
  - P_α determines station availability; α is nominal link attenuation and $\Delta\alpha$ is weather attenuation uncertainty (when available)

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Link Analysis Using Weather Model

- Analyze link using -α (dB) for atmospheric transmission and +/- $\Delta\alpha/2$ as the favorable and adverse tolerances
- Design link Initially for a "Link Summary" of 0 dB margin using nominal parameter values and calculate the favorable ($+\sigma_1$) and adverse ($-\sigma_2$) uncertainties
- Calculate "Recommended Link Margin" based on the adverse link uncertainty (i.e. margin = $2\sigma_2$)
- Redo link design with a nominal link margin equal to the "Recommended Link Margin"
  - Uses visibility data as a basis for link loss and link loss uncertainty
  - Provides a formal basis for establishing value of link margin

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Link Analysis Example

Link Design Control Table

Parameter	Nominal	Fav	Adv
Transmit laser power	**XXX**	**FFF**	**AAA**
Transmit aperture dia	...	...	...
•	•	•	•
•	•	•	•
•	•	•	•
Atmospheric Trans. (dB)	$-\alpha$	$\Delta\alpha/2$	$-\Delta\alpha/2$
•	•	•	•
Link Summary (0 dB Margin)	**0**	σ_1	$\boxed{-\sigma_2}$
Recommended Margin (dB)	$\boxed{2\sigma_2}$		

Note: 2.2σ corresponds to 97% confidence

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Link Availability Analysis

- Optical systems assume spatially-diverse reception
- Assume all ground stations are in independent weather cells (separated by few hundred km)
- Define a station as a "Candidate Station" if it can see spacecraft when atmosphere removed and above some minimum elevation angle (say 20 degrees)
- Define a station as "Available" if it is a candidate station and it has clear weather (i.e. atmospheric attenuation < α)

T4 34

Link Availability Analysis (Cont)

If N stations are "Candidate Stations", then the probability that m of them are "Available" is

$$P_N(m) = \binom{N}{m} (P\alpha)^m (1-P\alpha)^{N-m}$$

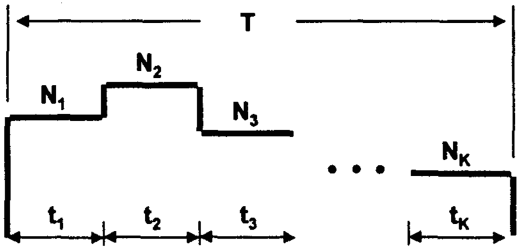
and the probability that <u>at least one</u> of the N stations is able to receive the link is

$$P_N = \sum_{m=1}^{N} P_N(m) = 1-(1-P_\alpha)^N$$

T4 35

Link Availability Analysis (Cont)

Next, consider total time (T) of spacecraft support "pass". Let N_1 be the number of candidate stations at the beginning of this time, and let the number of candidate stations change with time over the pass duration from N_1 (at the beginning) to N_K at the end of the pass.



Let the corresponding times of N_i candidate stations be t_i

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Link Availability Analysis (Cont)

Then, the daily "Expected Data Volume" (EDV) returned for the link considered above, with the weather and station configuration being considered is

$$\mathrm{EDV} = R \sum_{i=1}^{K} t_i P_{Ni}$$

where "R" is the data rate in the link design control table

RECOMMENDATION : Use EDV for RF/Optical comparisons

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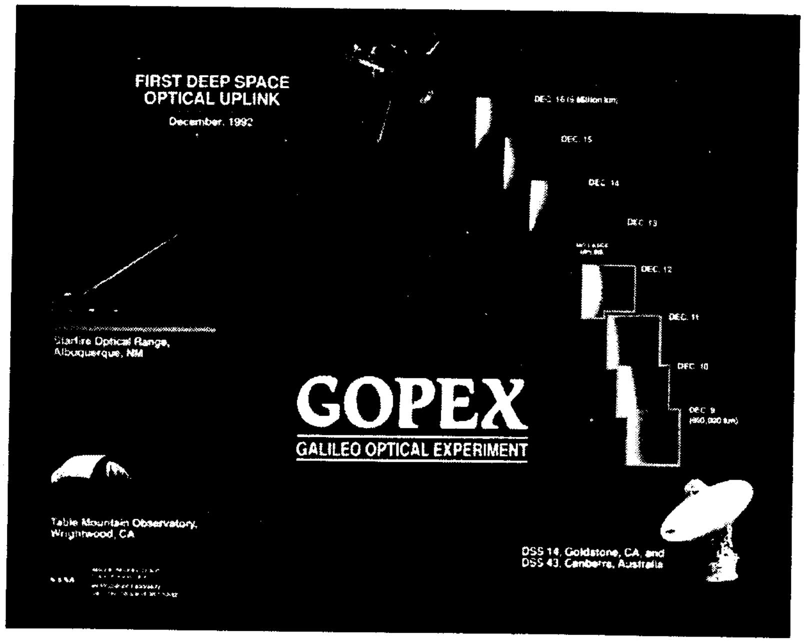
Recent Demonstrations

T4 38


FIRST DEEP SPACE
OPTICAL UPLINK
December, 1992
Starfire Optical Range,
Albuquerque, NM
GOPEX
GALILEO OPTICAL EXPERIMENT
Table Mountain Observatory,
Wrightwood, CA
DSS 14, Goldstone, CA, and
DSS 43, Canberra, Australia

T4 39

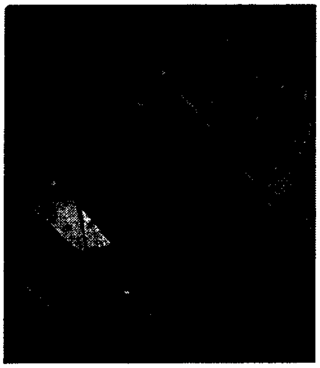

GOLD
GROUND-TO-ORBIT LASER-COM DEMONSTRATION

T4 40

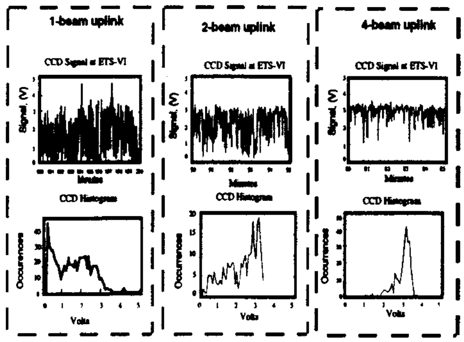
Ground-Orbit Lasercom Demo (GOLD)

GOLD Multiple-beam Transmission

- **Multiple beam uplink mitigates effects of atmospheric scintillation and beam wander**
  - **Beams are propagated through different atmospheric coherent cells**
  - **Each beam is delayed relative to the other by greater than laser's coherence length**



TMF 0.6-m Transmitter Telescope



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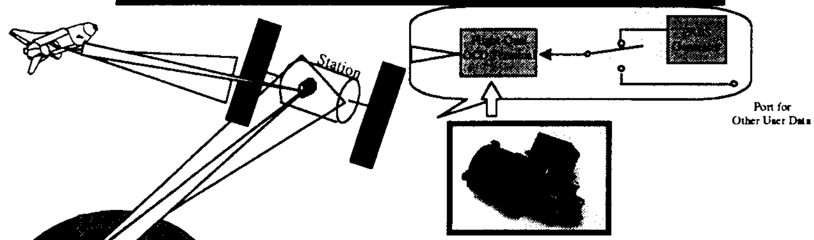
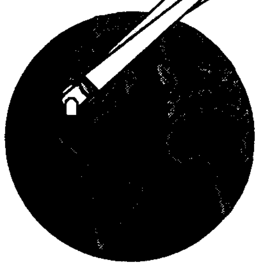
Future Demonstrations

T4 42

Demonstration from ISS



* OCD = Optical Communications Demonstrator



- PN Data dumped to ground at 1 Gbps when over ground site
    - Ground transmits beacon laser to ISS
    - ISS Terminal uses beacon to point downlink
- Station optical comm terminal can also dump other science data to ground
- Can demonstrate space-to-space optical comm if second optical terminal on Shuttle

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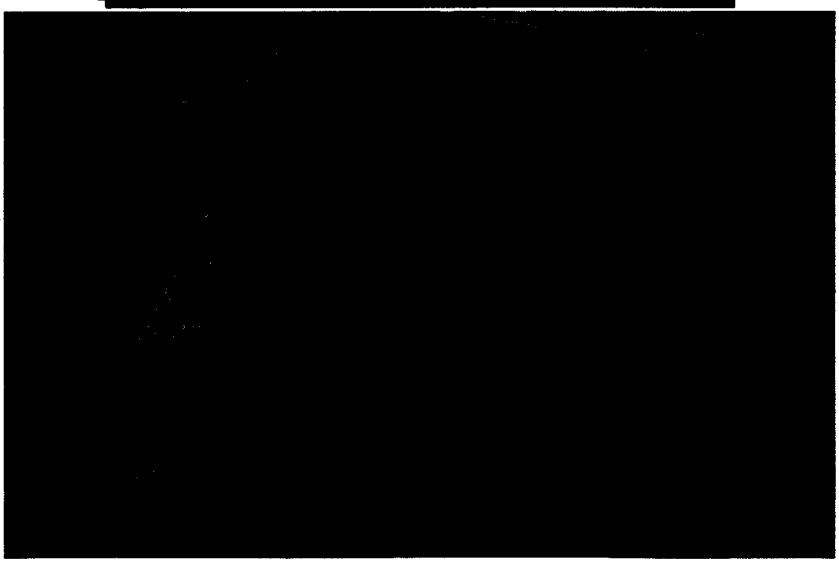
Location of Flight Terminal



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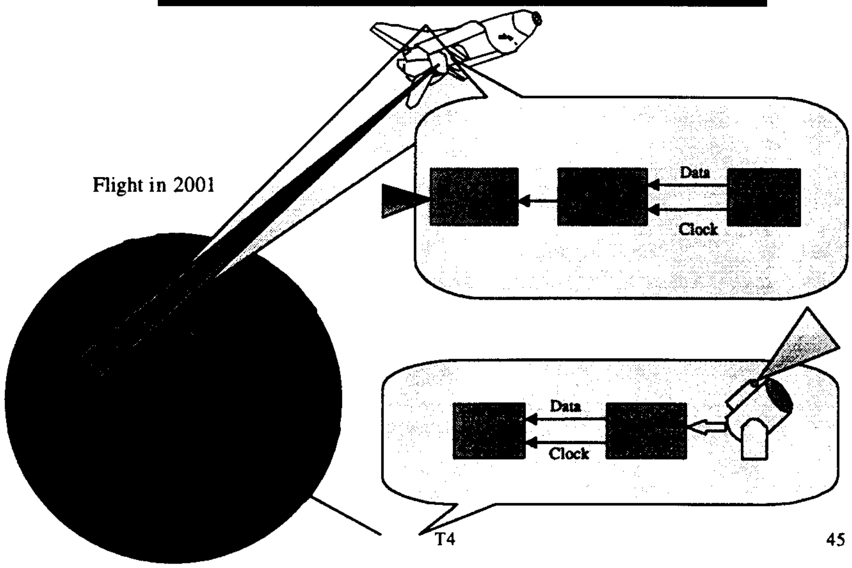
FOCAL Demonstration

FOCAL - A Free-space Optical Communications Assessment Link Demo



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Shuttle Link to Ground

1.6 Gbps

Transmit Laser Power	100	mW
Transmit Telescope Dia. (Space)	10	cm
Link Range (Slant range)	1050	km
Receive Telescope Dia. (Ground)	1	m
Atmospheric Losses (space-ground)	7	dB
System Losses	5.2	dB
Detector Efficiency	60	%
Data Rate	1.6	Gbps
Link Margin	21.3	dB

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